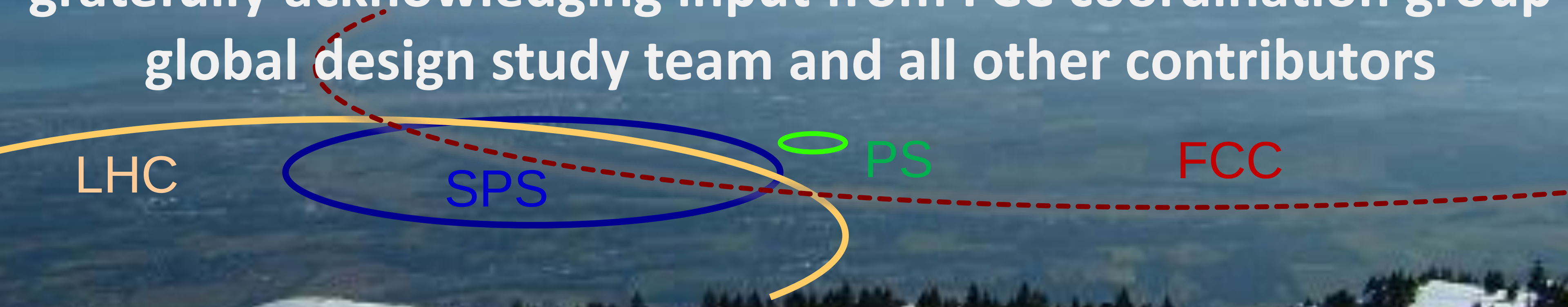
Future Circular Collider Study

Status and Parameter Update

M. Benedikt

gratefully acknowledging input from FCC coordination group
global design study team and all other contributors



http://cern.ch/fcc

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*

Outline

Introduction

- Motivation and Scope
- Study Timeline

Study Progress

- Implementation and Layout
- Machine parameters and optics
- Machine-Detector Activities, Technologies

FCC Collaboration Status

Outlook

FCC Strategic Motivation

- **European Strategy for Particle Physics 2013:**

  "…to **propose an ambitious post-LHC accelerator project**….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines….coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,…."

- **US P5 recommendation 2014:**

  "….A very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window…."

- **ICFA statement 2014:**

  "…. ICFA supports studies of energy frontier circular colliders and encourages global coordination.…"

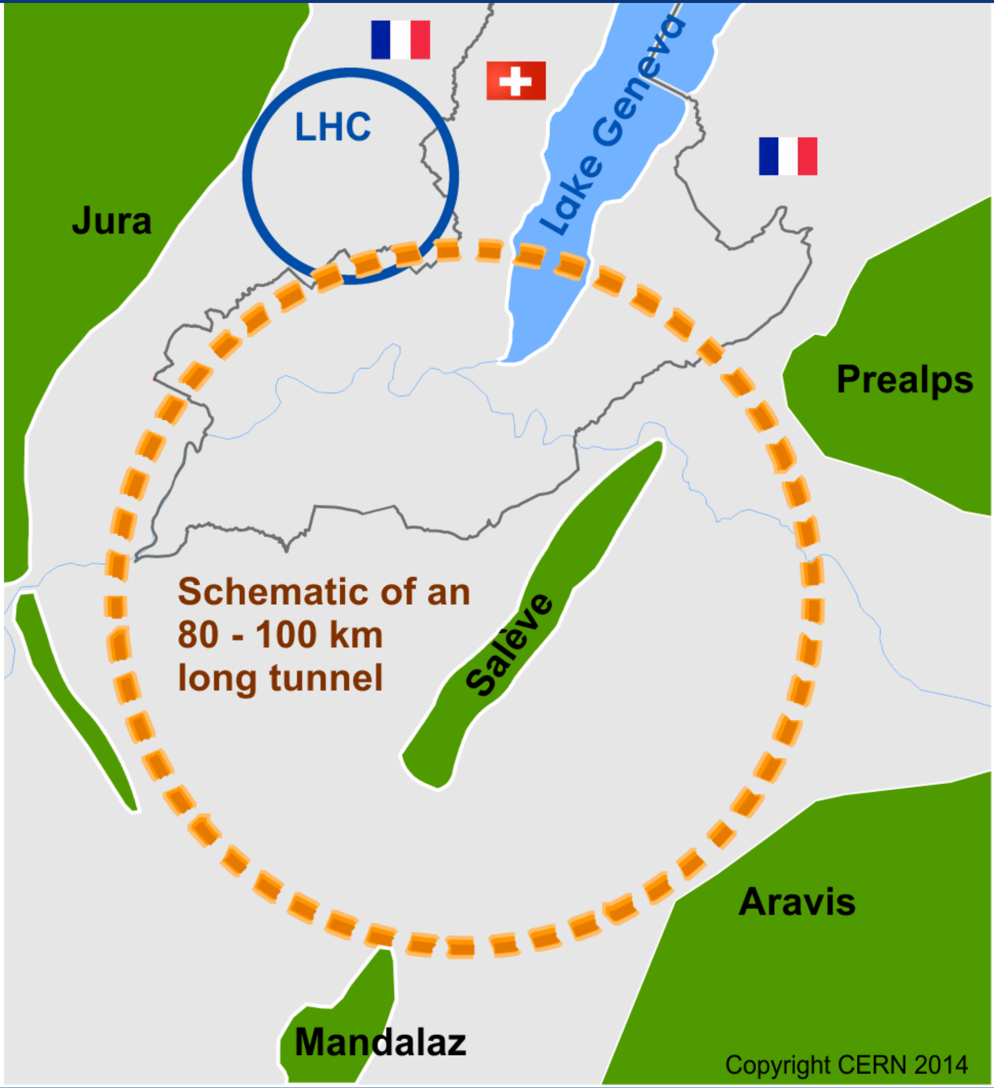
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

International FCC collaboration (CERN as host lab) to study:

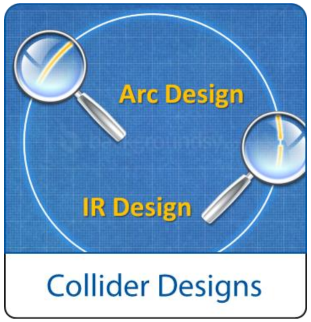
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*)** as potential first step
- ***p-e* (*FCC-he*) option**
- **HE-LHC** with *FCC-hh* technology

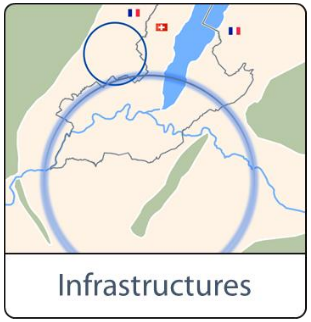


FCC Scope: Accelerator and Infrastructure



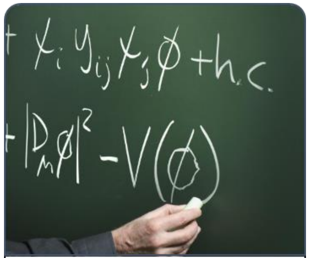
FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
HE-LHC: **based on FCC-hh technology**

key technologies
pushed in dedicated R&D programmes, e.g.
16 Tesla magnet program
SRF technologies and RF power sources



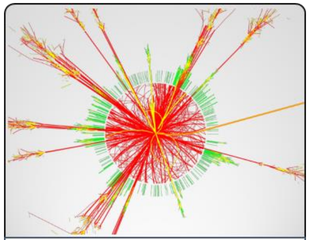
tunnel infrastructure in Geneva area, linked to CERN accelerator complex;
site-specific, as requested by European strategy

FCC Scope: Physics & Experiments



Physics Cases

physics opportunities for hh, ee and he
discovery potentials



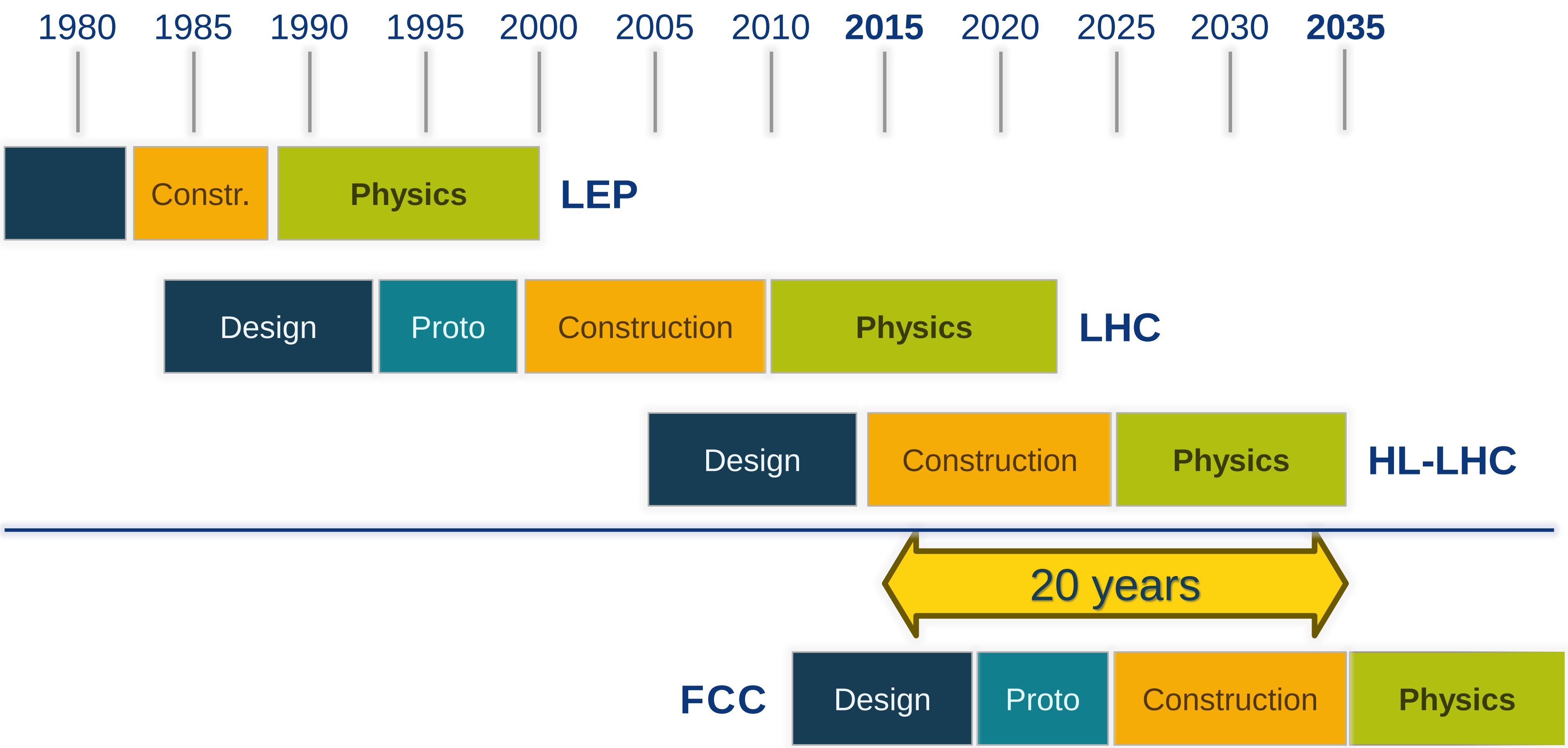
Experiments

experiment concepts for hh, ee and he
machine Detector Interface studies
concepts for **worldwide data services**

Cost Estimates

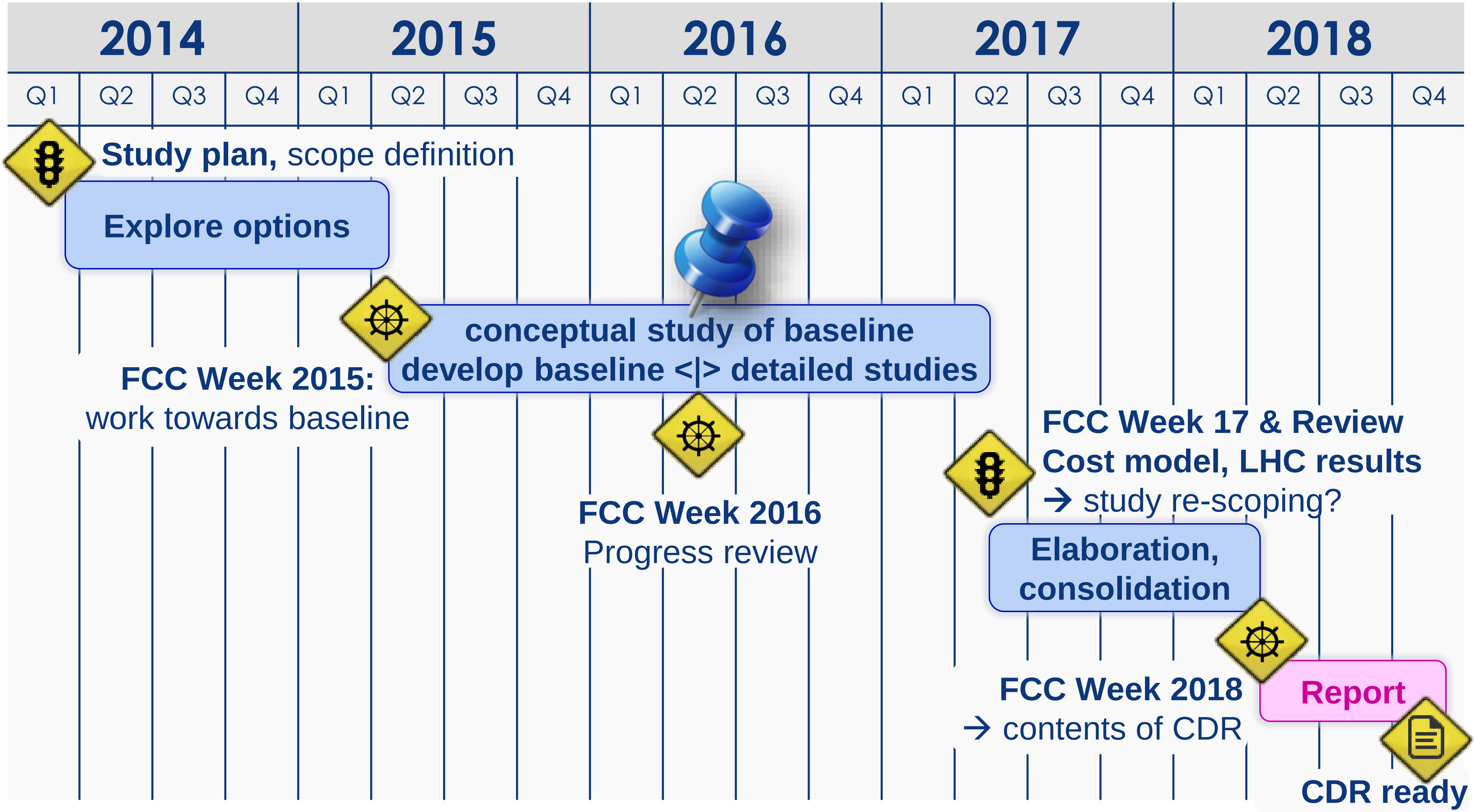
overall cost model ;
cost scenarios for collider options
including infrastructure and injectors ;
implementation and governance models

CERN Circular Colliders & FCC



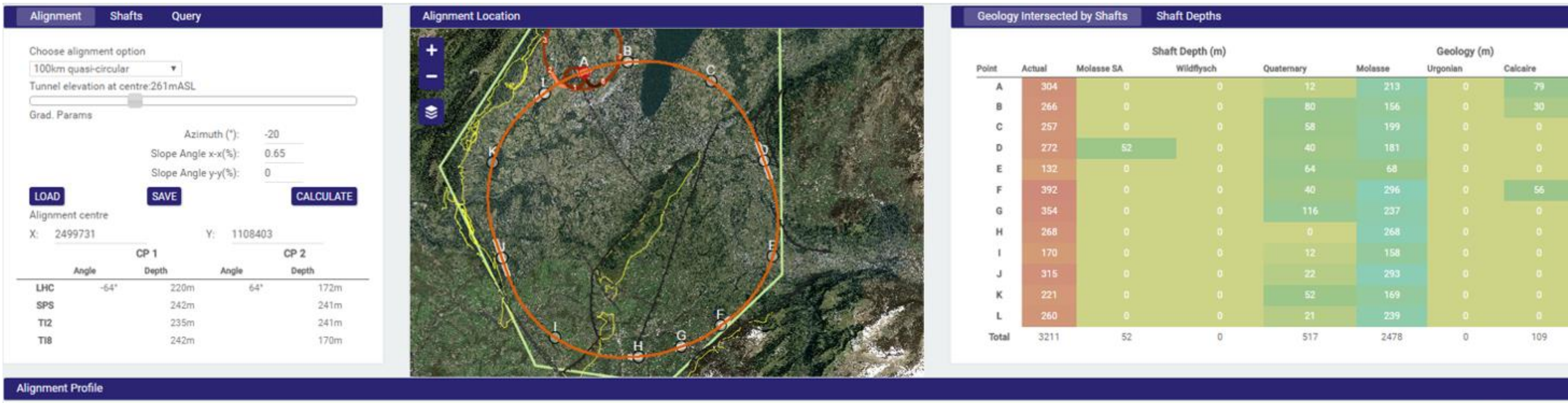
Now is the time to plan for the period 2035 – 2040

CDR Study Time Line



Status and Progress

Progress on site investigations



	CP 1 Angle	CP 1 Depth	CP 2 Angle	CP 2 Depth
LHC	-64°	220m	64°	172m
SPS		242m		241m
TI2		235m		241m
TI8		242m		170m

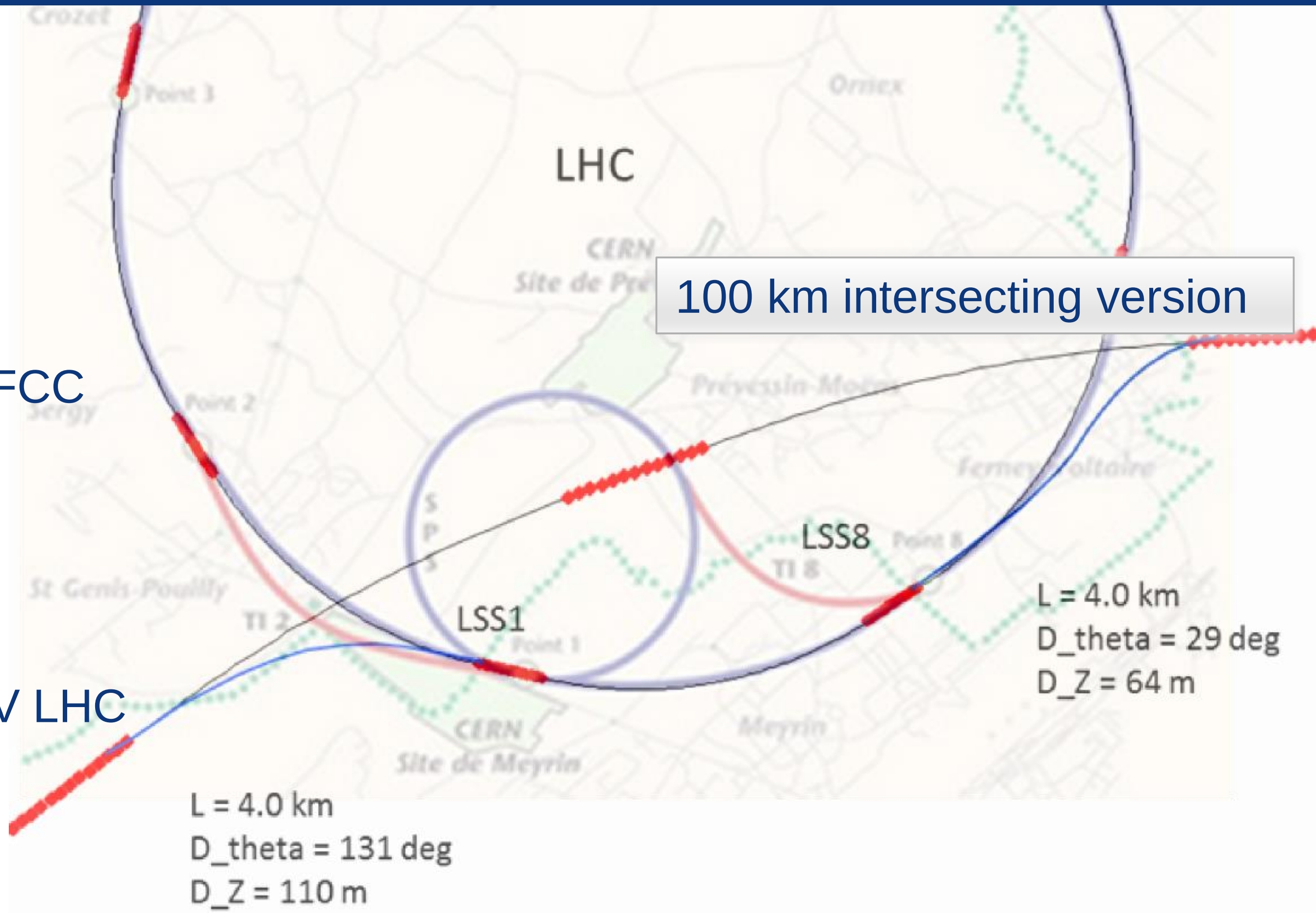
	Shaft Depth (m)	Geology (m)					
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	268	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

- 90 – 100 km fits geological situation well
- Review confirmed focus on 100 km, planar version
- LHC suitable as potential injector
- The 100 km version, intersecting LHC, is being studied now in more detail

FCC-hh injector studies

Injector options:

- **SPS → LHC → FCC**
- SPS/$SPS_{upgrade}$ → FCC
- SPS -> FCC booster → FCC



Current baseline:

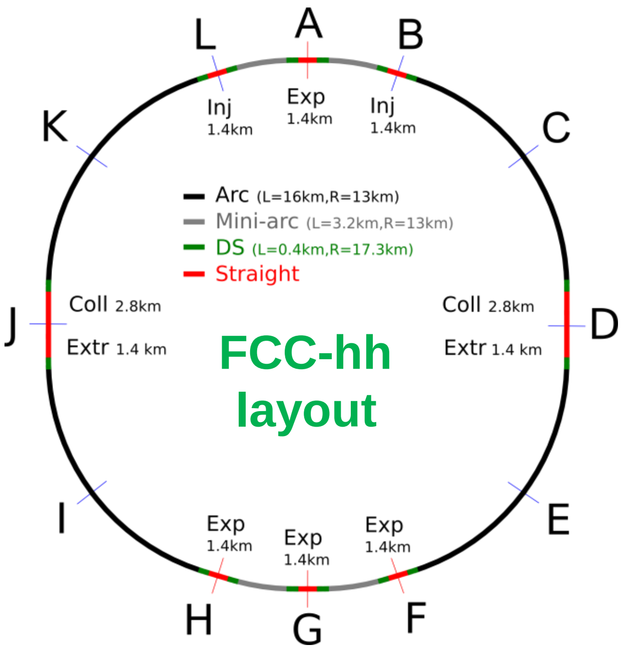
- injection energy 3.3 TeV LHC
- confirmed by review

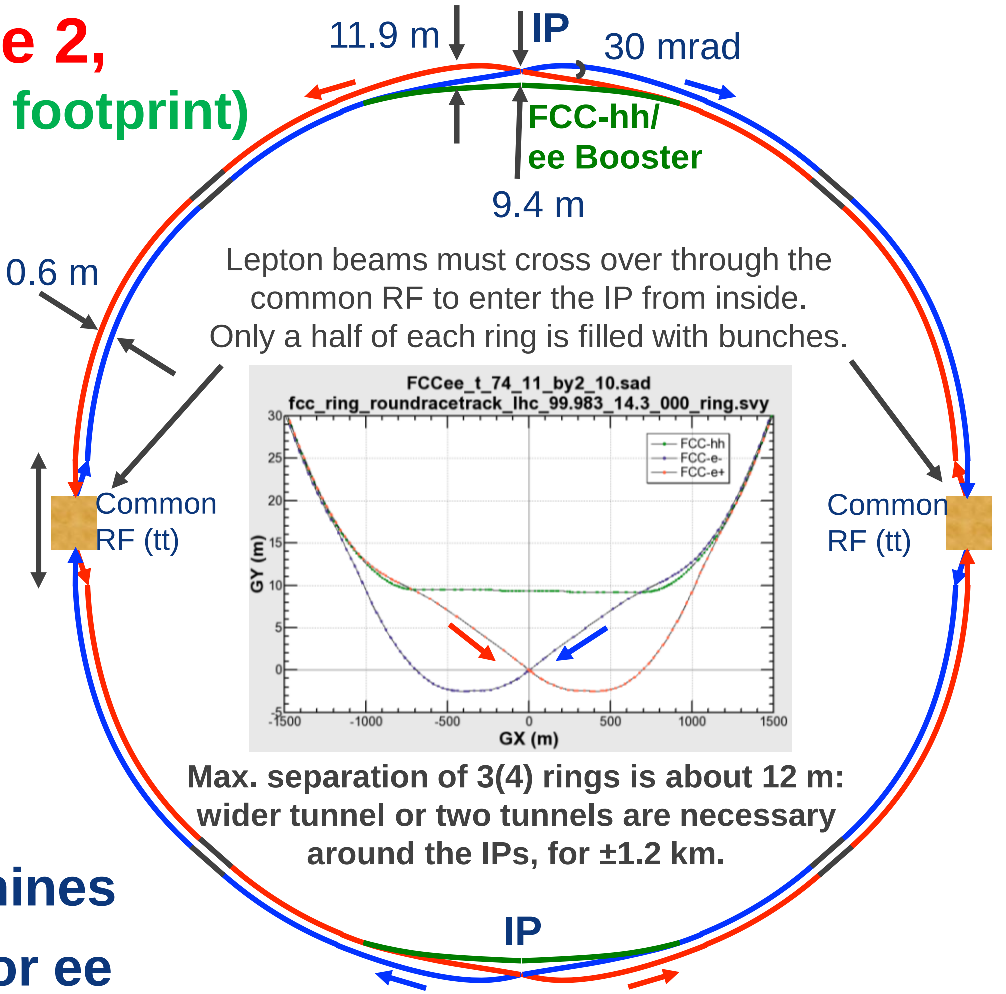
Alternative options:

- Injection around 1.5 TeV
- compatible with: $SPS_{upgrade}$, LHC, FCC booster

Common layouts for hh & ee

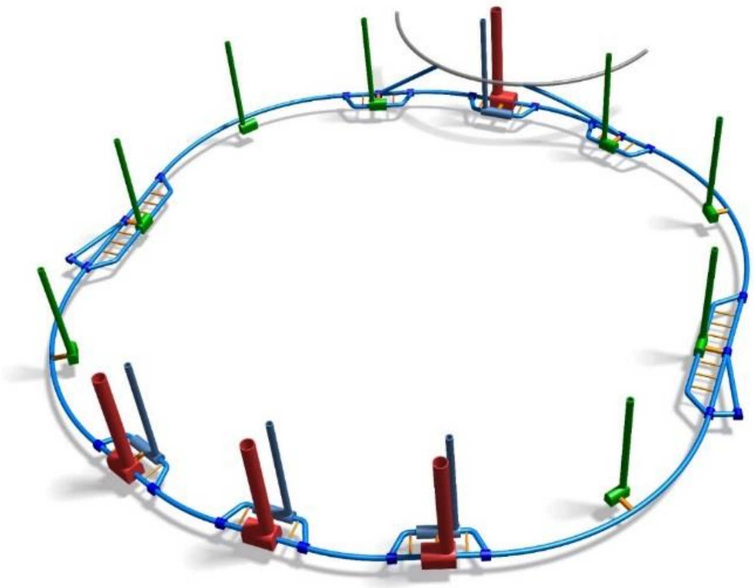
FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)

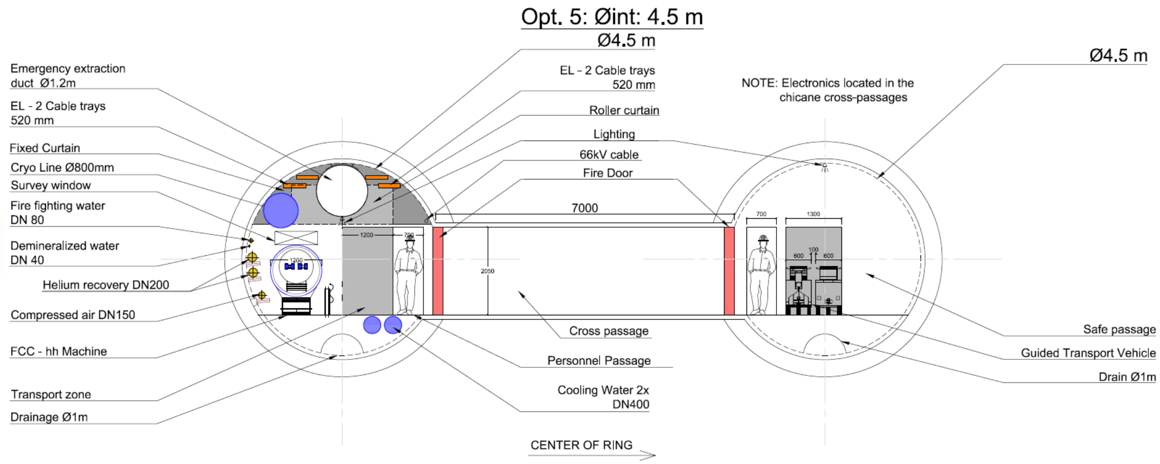


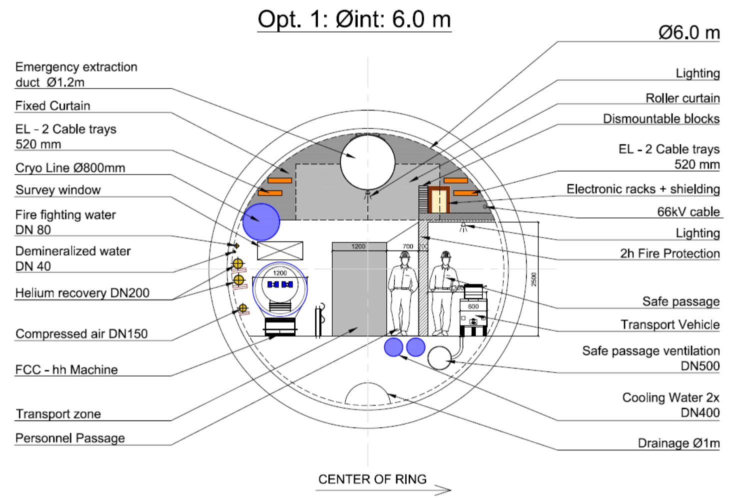


- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

Further CE and TI optimisation







More detailed studies launched on

- CE: single vs. double tunnels
- CE: caverns, shafts, underground layout
- technical infrastructures
- safety, access
- transport, integration, installation
- operation aspects

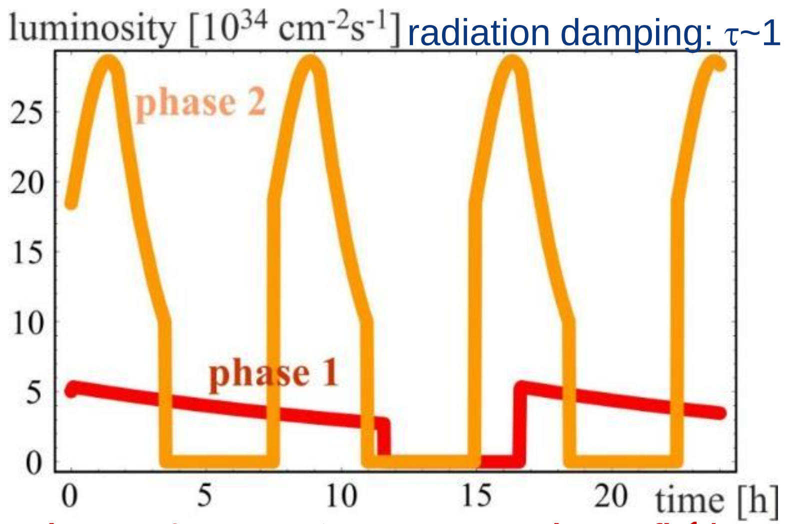
hadron collider parameters

parameter	FCC-hh		SPPC	HE-LHC* (*tentative)	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

FCC-hh operation & luminosity

5 year long operation periods

- 3.5 years operation periods with
  - 1 year HW comm., MDs, short stops
  - 2.5 years lumi. run with 70% availability
- 1.5 year shutdown



phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h, 1 ab^{-1} / year

2 periods at baseline parameters (10 yrs)

- **Peak luminosity 5×10^{34}cm^{-2}s^{-1}**
- **Total of 2.5ab^{-1} (per detector)**

3 periods at ultimate parameters (15 yrs)

- **Peak luminosity <=30×10^{34}cm^{-2}s^{-1}**
- **5ab^{-1} per period total of 15ab^{-1}**

O(20) ab^{-1} integrated luminosity/experiment

consistent with physics goal: 20 ab^{-1} in total

Detectors must sustain a total of >20ab^{-1} and >5ab^{-1} between maintenance stops
Machine design to support 3.5 year operation periods w/o warm up or long stops

Physics prospects

Physics at the FCC-hh

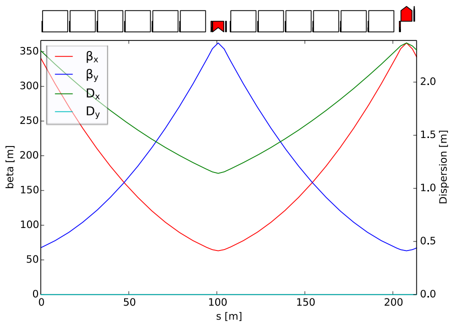
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages)
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages)
- **Volume 3: beyond the Standard Model phenomena** (189 pages)
- **Volume 4: physics with heavy ions** (56 pages)
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

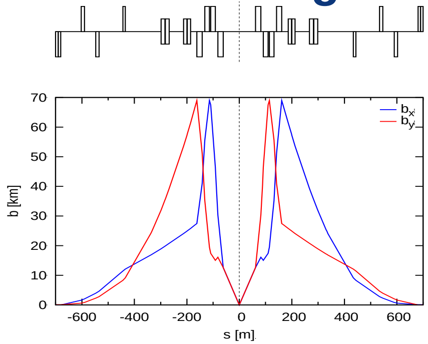
- **will be published as CERN yellow report**
- **paper copies available at registration desk**

FCC-hh full-ring optics design

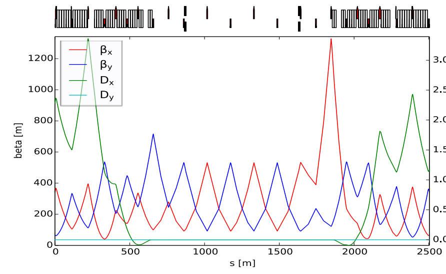
Regular arc cell



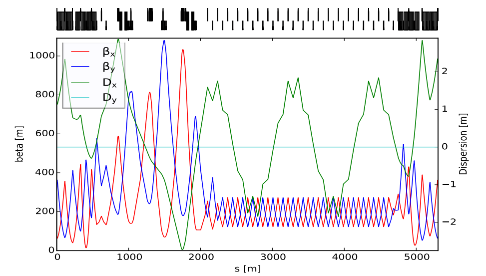
Interaction region

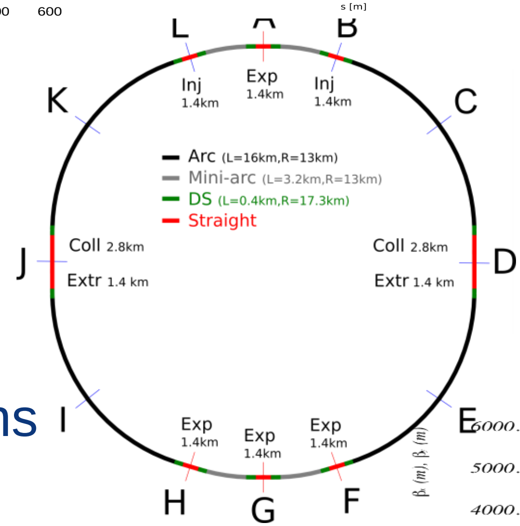


Injection with RF

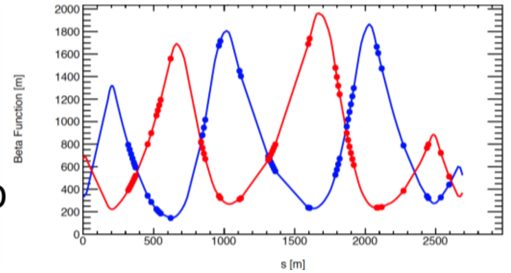


Momentum collim.

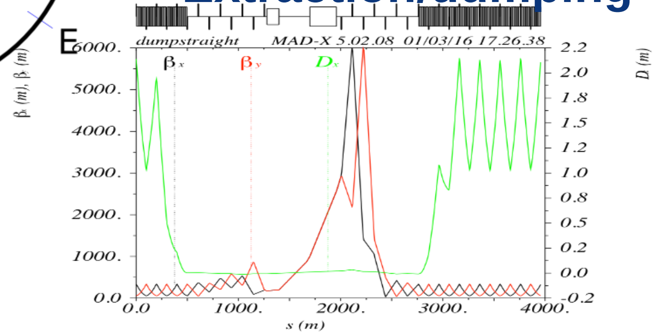




Betatron collimation



Extraction/dumping



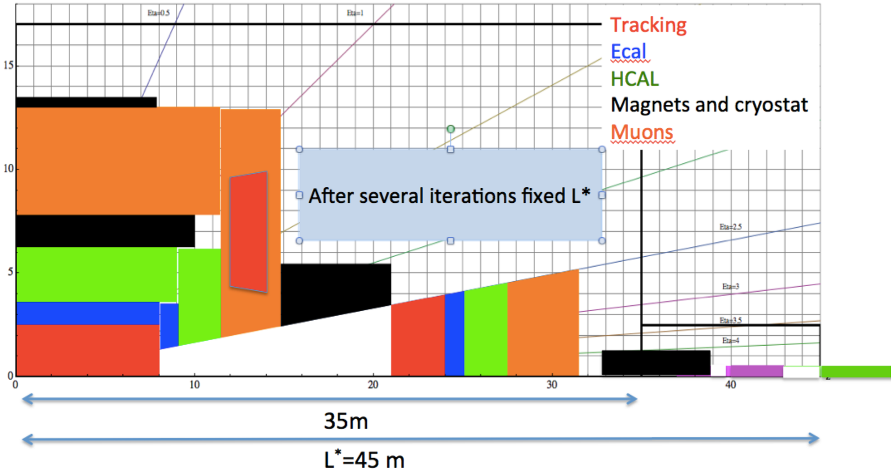
Full ring optics design available as basis for:

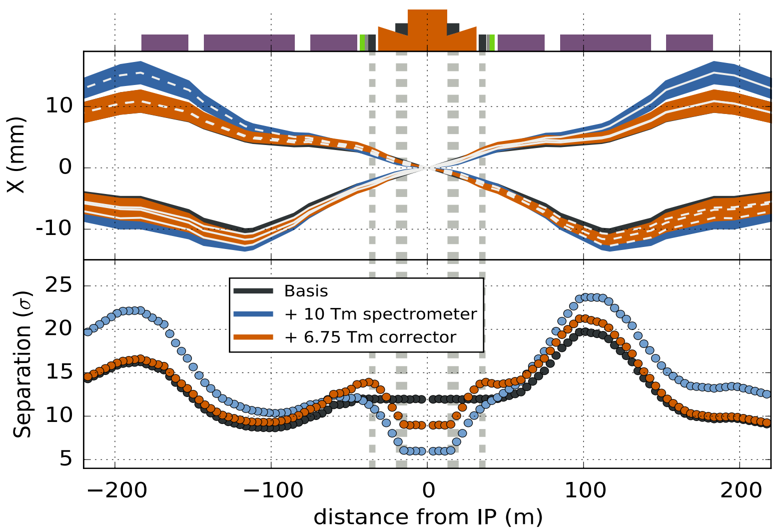
- beam dynamics studies
- optimisation of each insertion
- definition of system specifications (apertures, etc.)
- improvement of baseline optics and layout

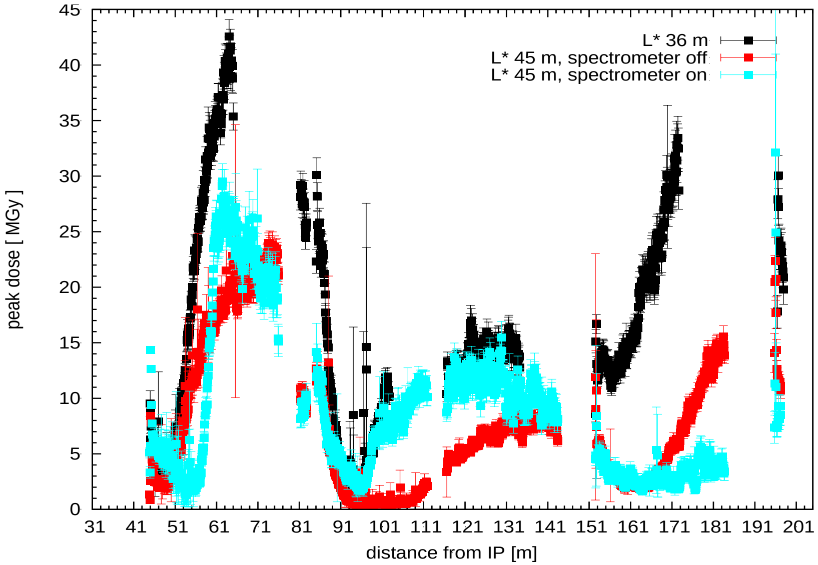
FCC-hh MDI status

Design of interaction region

- consistent for machine and detector
  - L^*=45 m
  - integrated spectrometer and compensation dipoles
- new optics design with longer triplet with large aperture
  - should help for collision debris
  - more beam stay clear

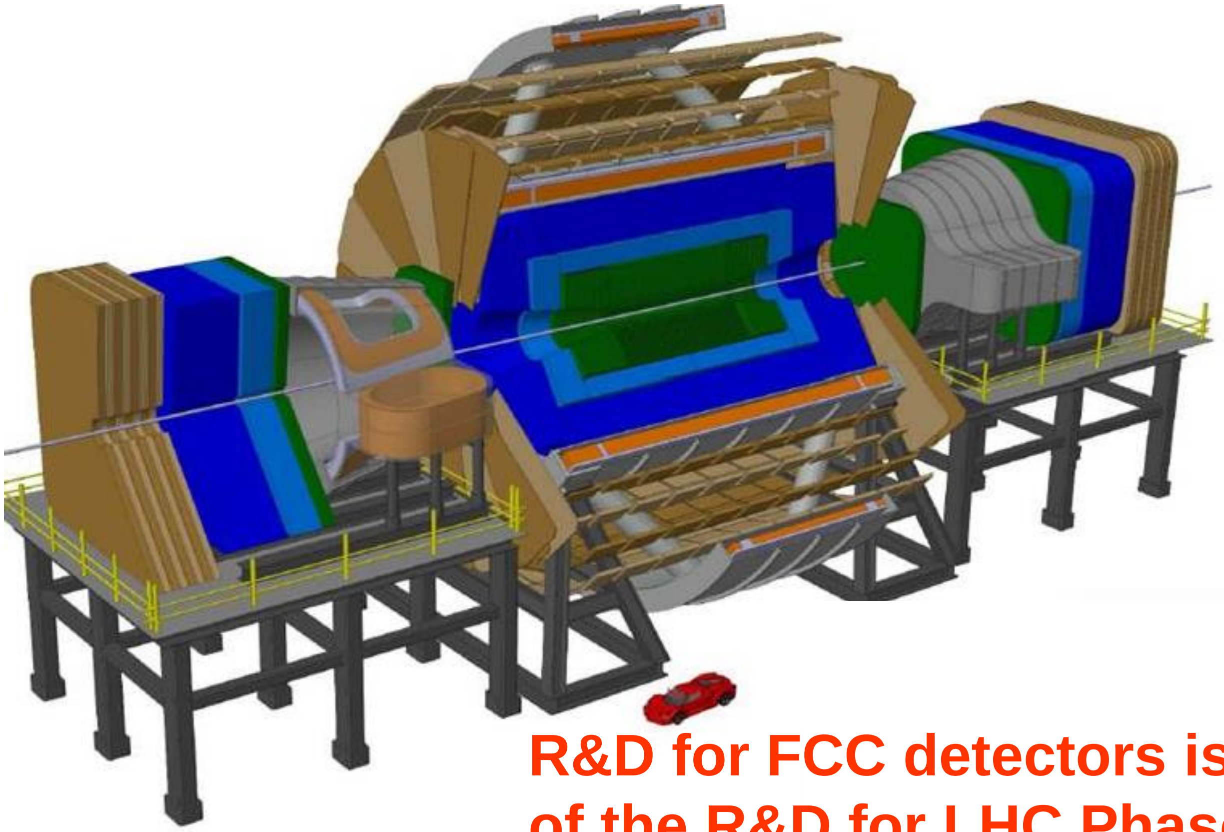






Detector Concepts for 100 TeV pp

A B=6 T, R=6 m solenoid with shielding coil and 2 dipoles has been engineered in detail.
Different alternative magnet systems are also being explored.



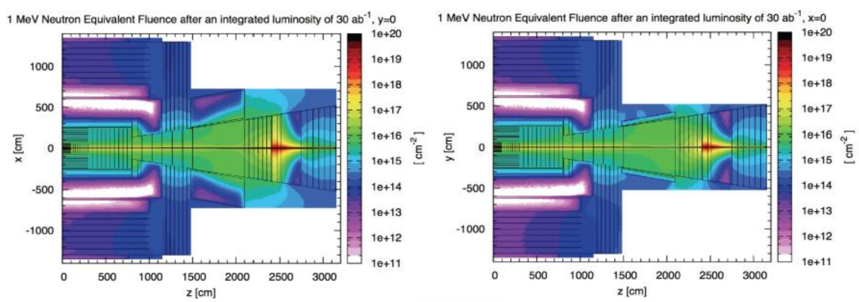
Some design challenges:

- large η acceptance
- radiation levels of >50 x LHC Phase II
- pileup of ~1000

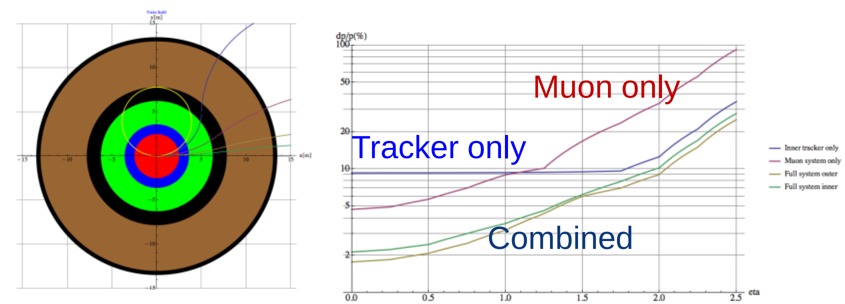
R&D for FCC detectors is a natural continuation of the R&D for LHC Phase II upgrade

Detector studies & simulation framework

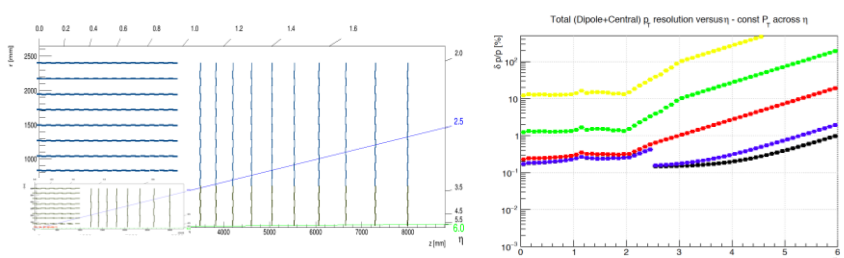
- **Detector studies well under way for hh and ee**
- **Parametrized detector performance model (DELPHES) available and integrated in FCC software framework for physics simulations**
  https://twiki.cern.ch/twiki/bin/view/FCC/FccPythiaDelphes



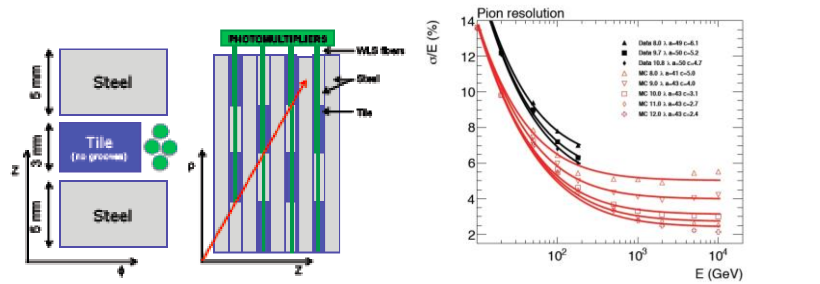
Radiation simulations, shielding requirements



Muon system performance & requirement studies



Tracker resolution, occupancy, data rate studies



Calorimeter resolution, containment studies

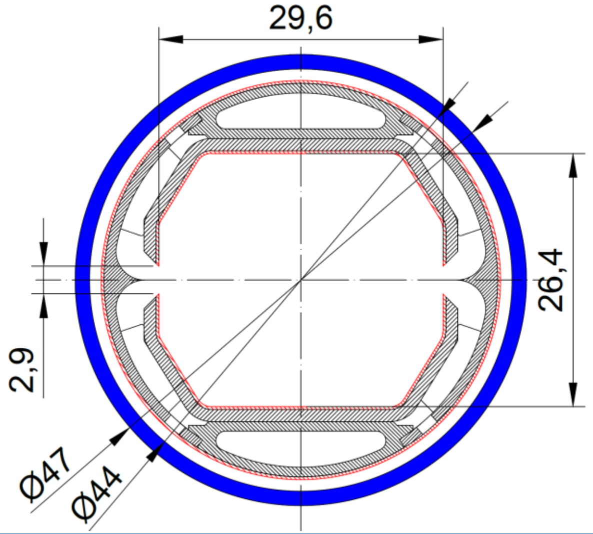
Synchrotron radiation/beam screen

High synchrotron radiation load of protons @ 50 TeV:

- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs**

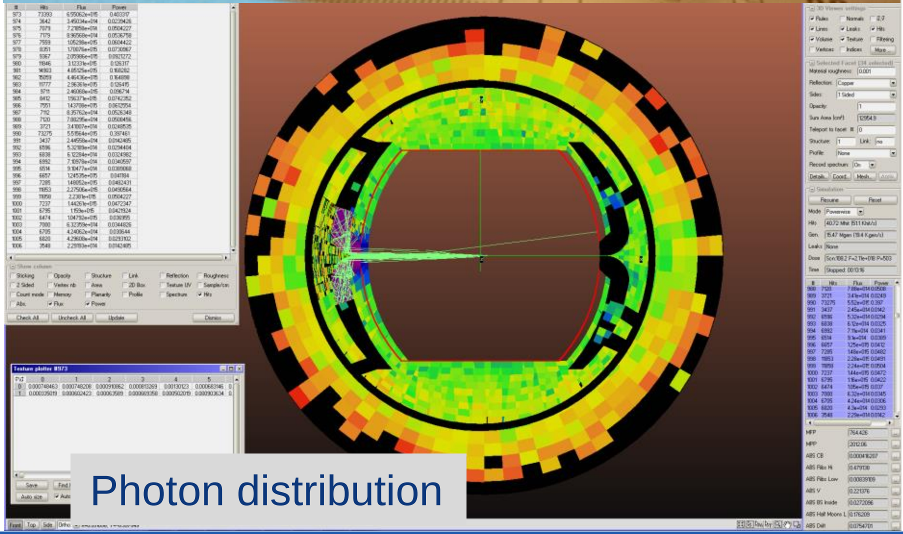
New Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- avoids photo-electrons, helps vacuum



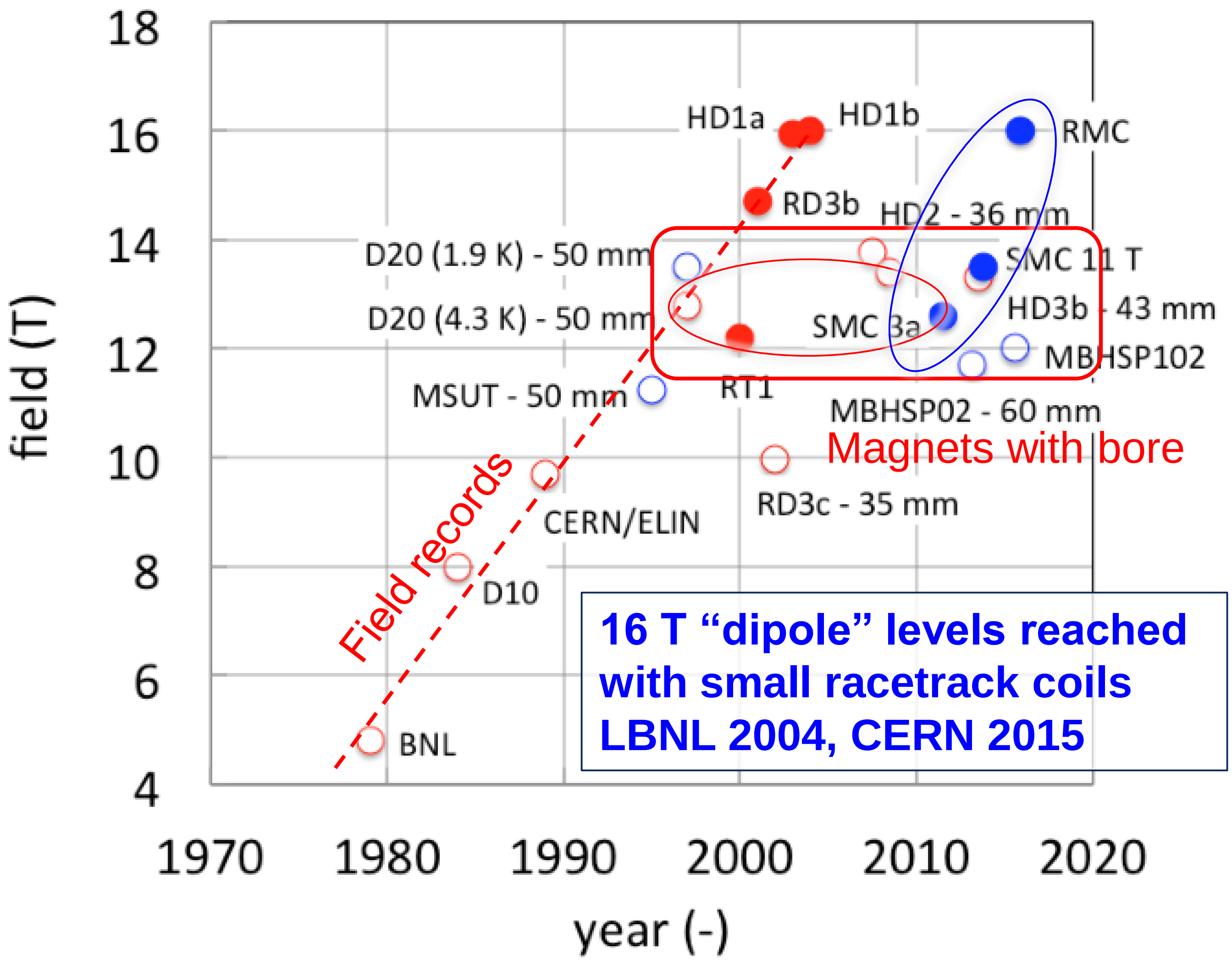
First FCC-hh beam screen prototype

Testing 2017 in ANKA within EuroCirCol



Photon distribution

CERN & EuroCirCol 16T programs



16 T "dipole" levels reached with small racetrack coils LBNL 2004, CERN 2015

LBNL HD1

CERN RMC

Nb_3Sn conductor program

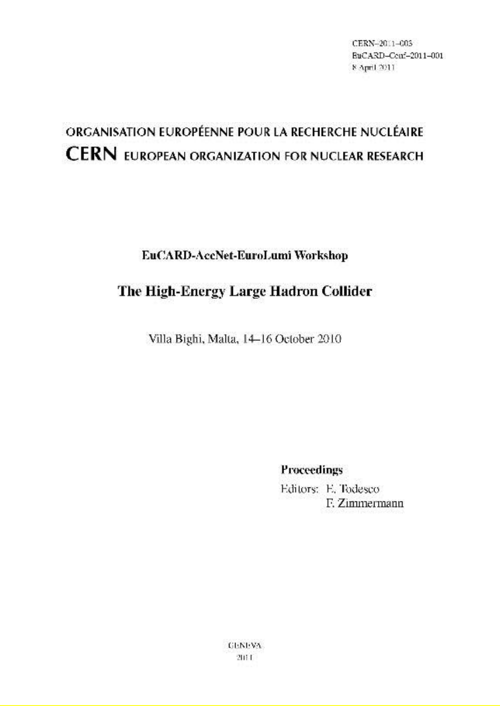
Nb_3Sn conductor is one of the major cost and performance factors for FCC-hh and must be given highest attention

- **Goals: J_c increase (16 T, 4.2 K) > 1500 A/mm^2, significant cost reduction**
- **Actions ongoing and planned (in addition to activities at CERN):**
  - Purchase of wires in Europe, US
  - Industrial R&D in Europe
  - Collaboration agreements with KEK, Russia, Korea (in preparation), to stipulate conductor development with regional industry
  - Collaborations with several European Universities and Research Centres
- **Strong industrial R&D program is highly desired also in the US**

High-Energy LHC

FCC study continues effort on **high-field collider in LHC tunnel**

2010 EuCARD Workshop Malta;
Yellow Report CERN-2011-1



CERN–2011–003
EuCARD–Conf–2011–001
8 April 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EuCARD-AccNet-EuroLumi Workshop

The High-Energy Large Hadron Collider

Villa Bighi, Malta, 14–16 October 2010

Proceedings
Editors: E. Todesco
F. Zimmermann

GENEVA
2011

EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider - HE-LHC10, E. Todesco and F. Zimmermann (eds.), EuCARD-CON-2011-001; arXiv:1111.7188; CERN-2011-003 (2011)

- **based on 16-T dipoles developed for FCC-hh**
- **extrapolation of other parts from the present (HL-)LHC and from FCC developments**

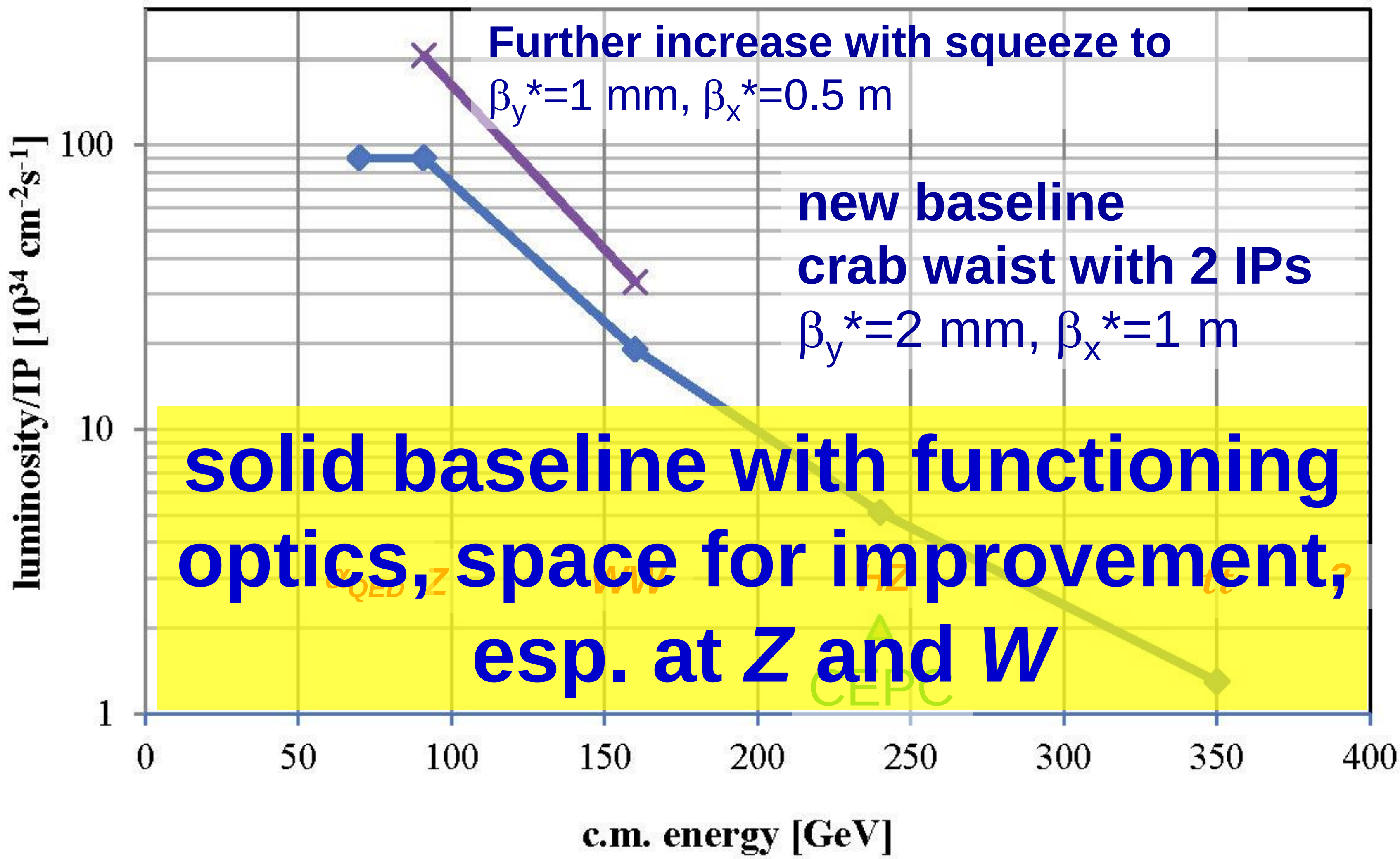
lepton collider parameters

parameter	FCC-ee (400 MHz)					CEPC	LEP2
Physics working point	Z		WW	ZH	tt_{bar}	H	
energy/beam [GeV]	45.6		80	120	175	120	105
bunches/beam	30180	91500	5260	780	81	50	4
bunch spacing [ns]	7.5	2.5	50	400	4000	3600	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	3.8	4.2
beam current [mA]	1450	1450	152	30	6.6	16.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3	2.0	0.0012
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.1	3.34
synchrotron power [MW]	100					103	22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	6.9	3.5

identical FCC-ee baseline optics for all energies

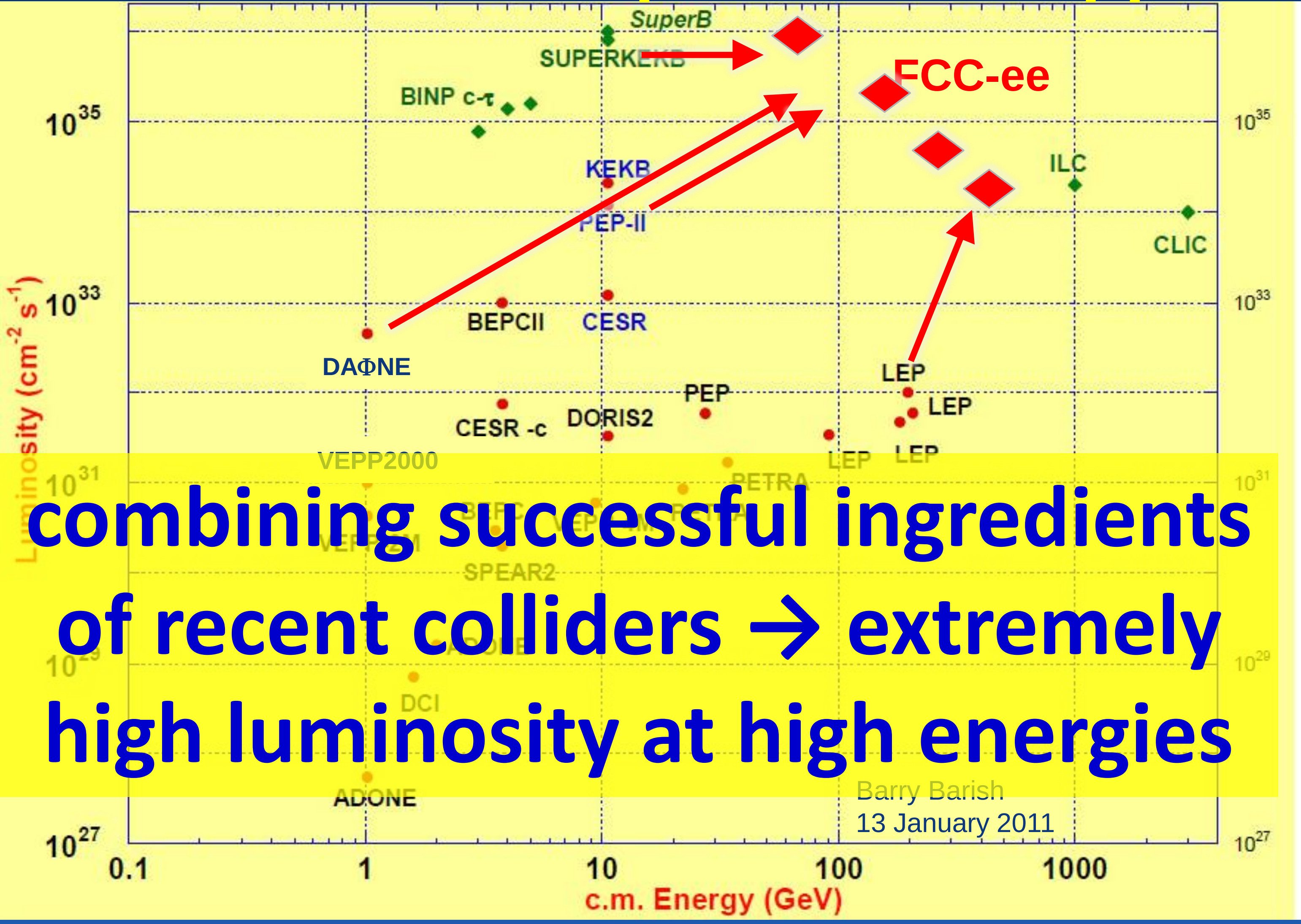
FCC-ee: 2 separate rings CEPC, LEP: single beam pipe

FCC-ee luminosity per IP



solid baseline with functioning optics, space for improvement, esp. at *Z* and *W*

FCC-ee exploits lessons & recipes from past e^+e^- and *pp* colliders



combining successful ingredients of recent colliders → extremely high luminosity at high energies

LEP:
high energy
SR effects

B-factories:
KEKB & PEP-II:
high beam currents
top-up injection
DAFNE: crab waist

Super B-factories
S-KEKB: low β_y^*

KEKB: e^+ source

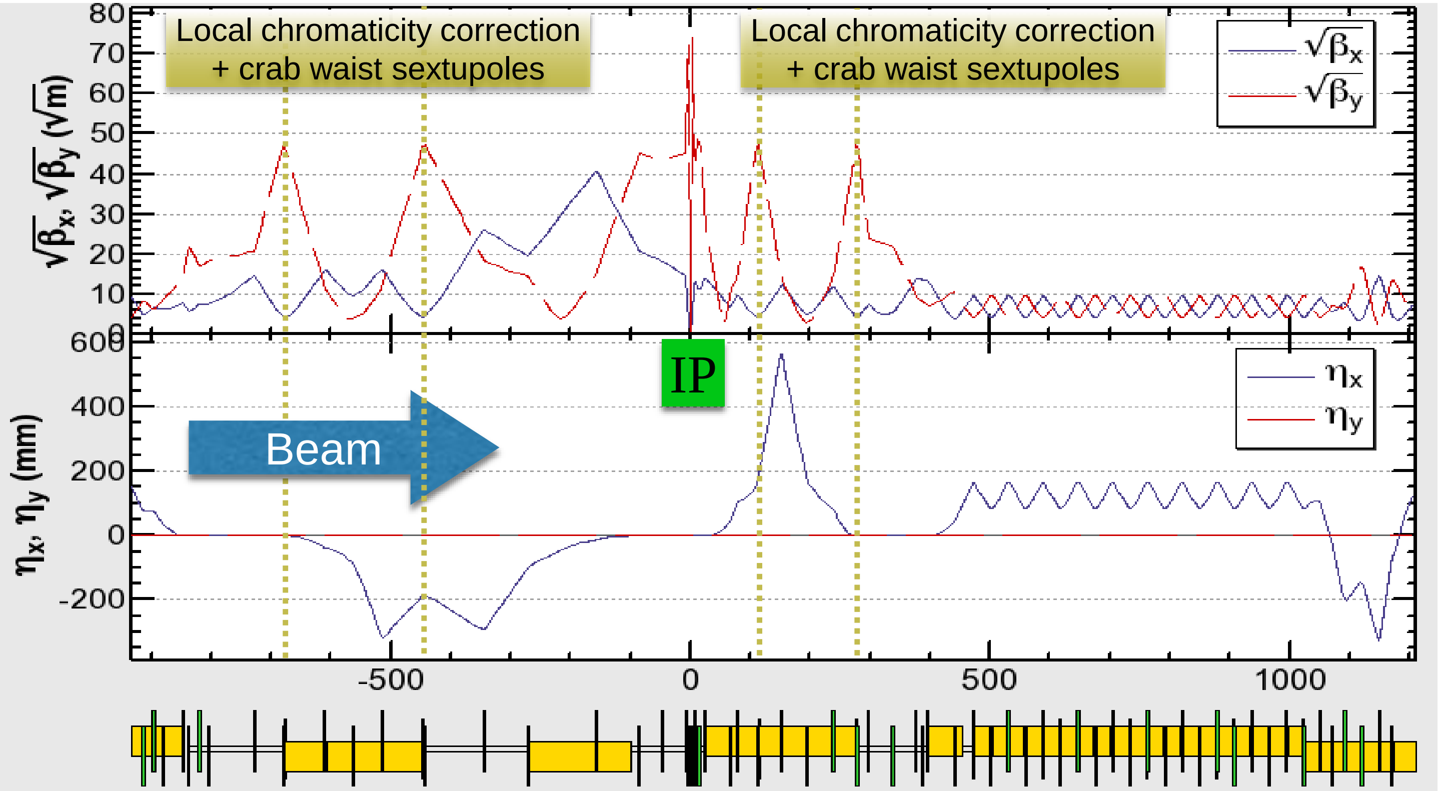
HERA, LEP, RHIC:
spin gymnastics

FCC-ee optics design

Optics design for all working points achieving baseline performance

Interaction region: asymmetric optics design

- Synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- Dynamic aperture & momentum acceptance requirements fulfilled at all WPs



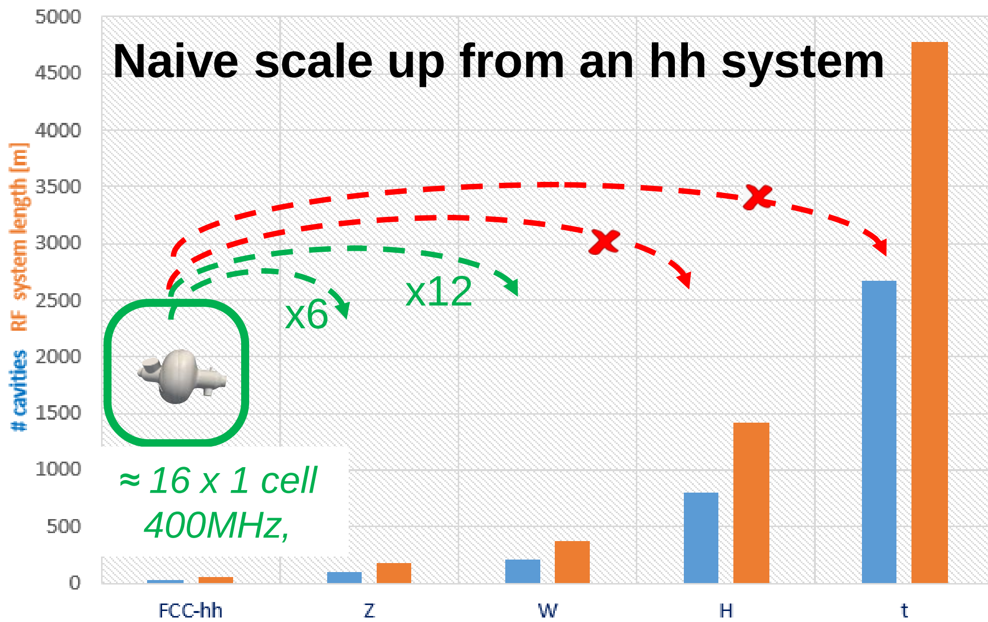
RF system requirements

Very large range of operation parameters

“Ampere-class” machines

	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
hh	0.032		**500**	
Z	0.4/0.2	30000/90000	**1450**	0.034
W	0.8	5162	152	0.33
H	**5.5**	770	30	1.67
t	**10**	78	6.6	7.55

“high gradient” machines

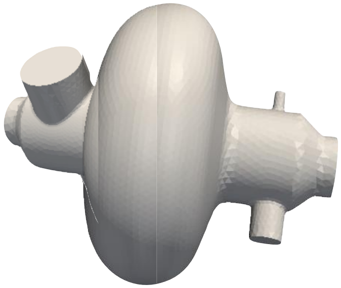


- Voltage and beam current ranges span more than factor > 10^2
- No well-adapted single RF system solution satisfying requirements

RF system R&D lines

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)

- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)



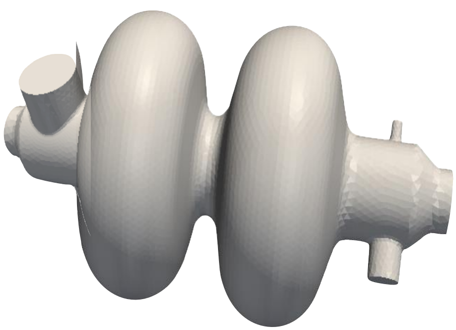
hh — ≈ 16 cells per beam

Z — ≈ 100 per beam (+ 100 for booster ring)

(**W** — ≈ 210 per beam (+ 210 for booster ring))

400 or 800 MHz multi-cell cavities preferred for ee-H, ee-tt and ee-W

- Baseline options 400 MHz Nb/Cu @4.5 K, ◄—► 800 MHz bulk Nb system @2K
- R&D: High Q_0 cavities, coating, long-term: Nb_3Sn like components



W — ≈ 200 per beam (+ 200 for booster)

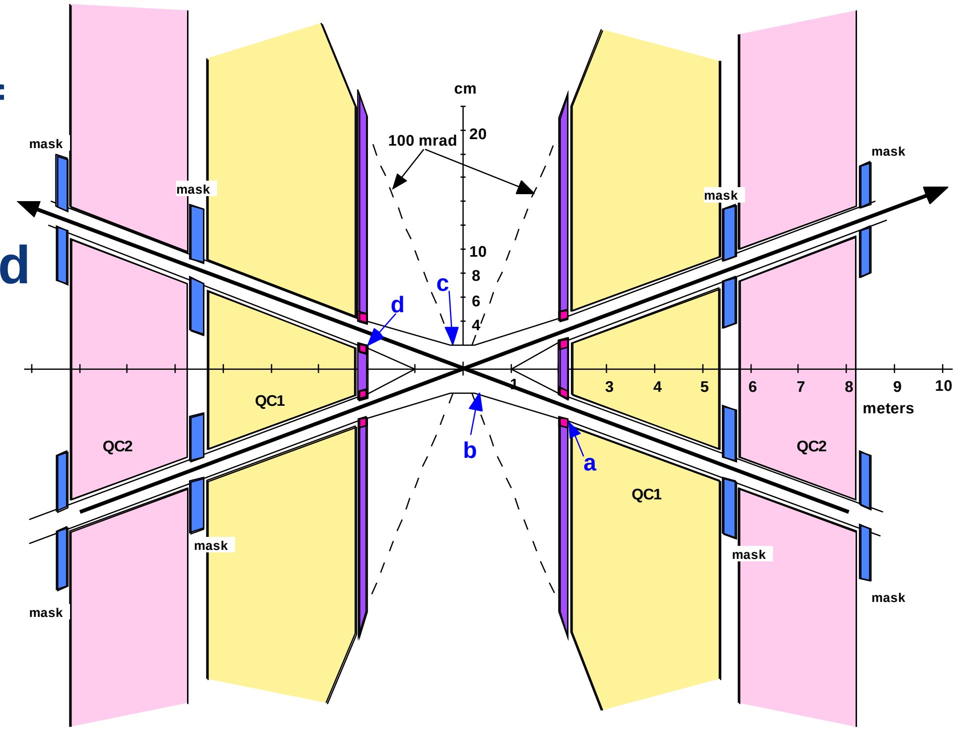
H — ≈ 800 per beam (+ 800 for booster)

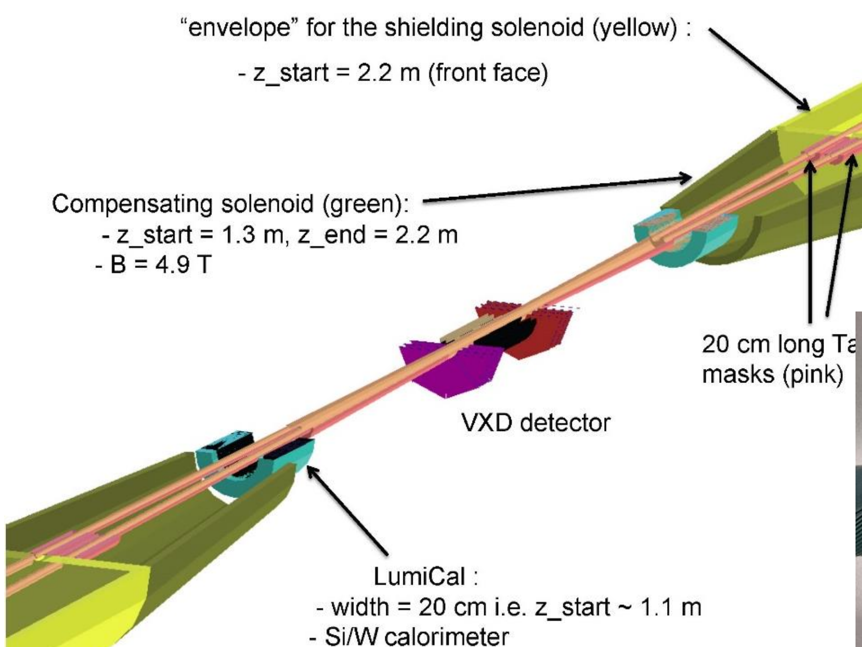
t — ≈ common 2600 cells for both beams (+ 2600 for booster)

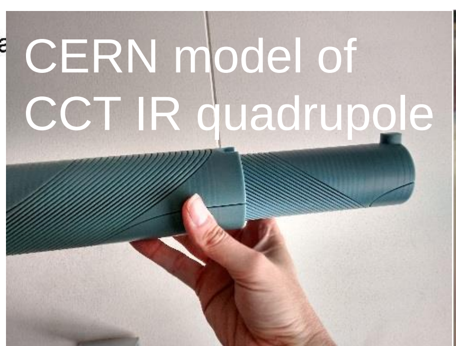
FCC-ee MDI optimisation

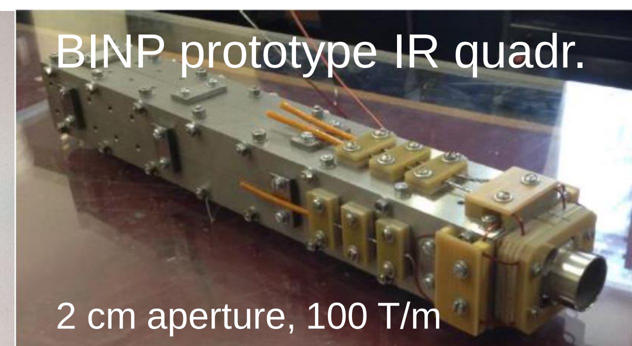
MDI work started with optimization of

- ***l**, IR quadrupole design**
- **compensation & shielding solenoid**
- **SR masking and chamber layout**









Design of FCC-ee Detectors

Adapted from ILC/CLIC detector: Experience with LEP detectors and ~20 years R&D for LC

Some physics differences

-- Lower maximum energy 400GeV vs. >1000 GeV

➔ Momentum & energy resolution requirements

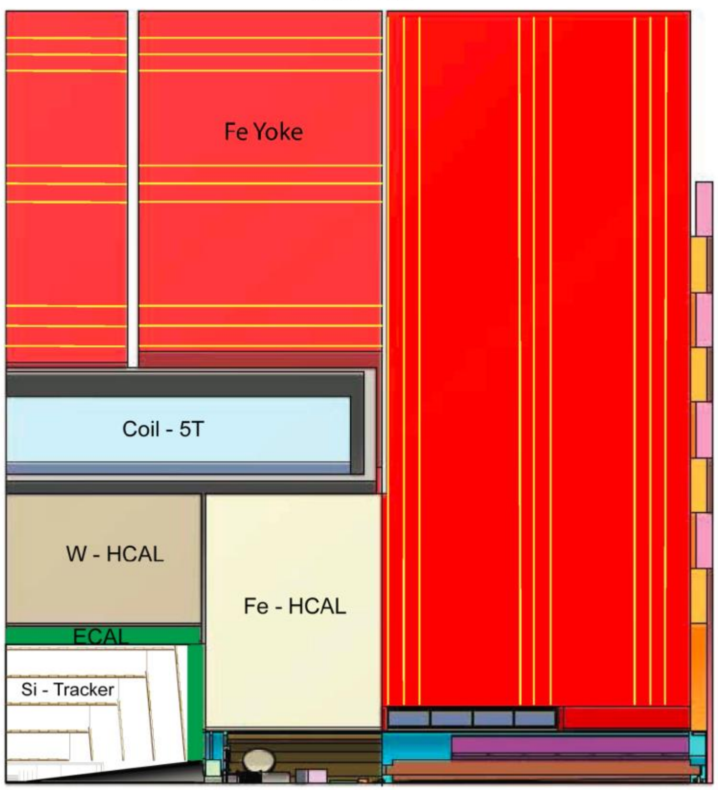
-- Higher statistics – need matching systematics

Some technical differences

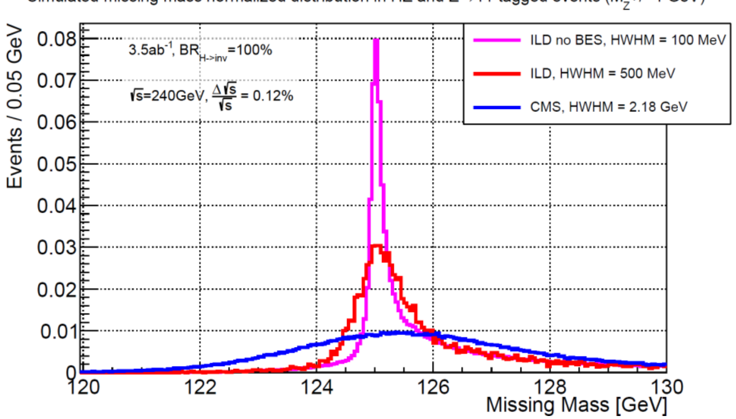
-- High physics rate: 100 kHz Zs, must keep all.

-- No bunching ➔ cooling issues

-- better definition of beam energy and lower beam induced backgrounds



Exemple: Improved Higgs missing mass due to lower σ_{Ecm} @ FCC-ee ➔



FCC International Collaboration

- **74 institutes**
- **26 countries + EC**

Status: April, 2016

FCC Collaboration Status

74 collaboration members & CERN as host institute, March 2016

ALBA/CELLS, Spain
Ankara U., Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
Cinvestav, Mexico
CNRS, France
CNR-SPIN, Italy
Cockcroft Institute, UK
U Colima, Mexico
UCPH Copenhagen, Denmark
CSIC/IFIC, Spain
TU Darmstadt, Germany
TU Delft, Netherlands
DESY, Germany
DOE, Washington, USA
ESS, Lund, Sweden
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland

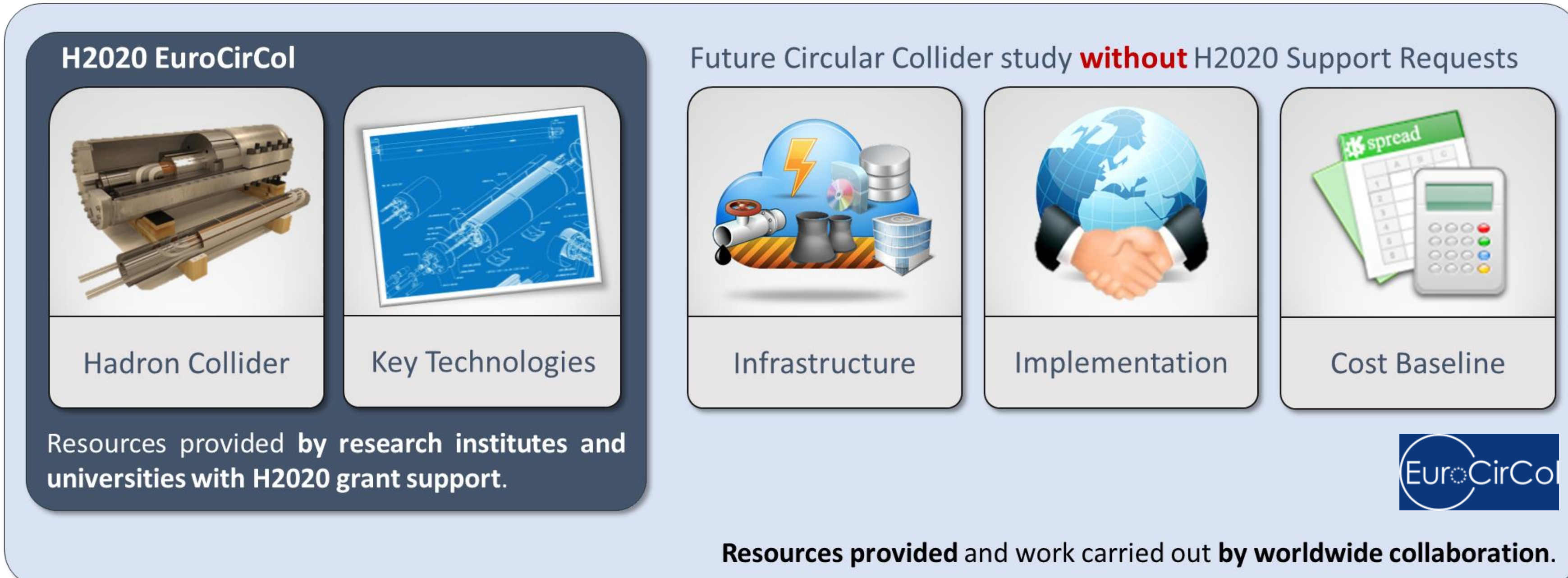
UT Enschede, Netherlands
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
GWNU, Korea
U. Guanajuato, Mexico
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
IIT Kanpur, India
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI, UK
JINR Dubna, Russia
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany

KU, Seoul, Korea
Korea U Sejong, Korea
U. Liverpool, UK
U. Lund, Sweden
MAX IV, Lund, Sweden
MEPhI, Russia
UNIMI, Milan, Italy
MIT, USA
Northern Illinois U, USA
NC PHEP Minsk, Belarus
U Oxford, UK
PSI, Switzerland
U. Rostock, Germany
RTU, Riga, Latvia
UC Santa Barbara, USA
Sapienza/Roma, Italy
U Siegen, Germany
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wigner RCP, Budapest, Hungary
Wroclaw UT, Poland

EuroCirCol EU Horizon 2020 Grant

EC contributes with funding to FCC-hh study

- Launched in June 2016, is in full swing now and makes essential contributions to the FCC-hh work packages:
- **Arc & IR optics design, 16 T dipole design, cryogenic beam vacuum system**
- **Recognition of FCC Study by European Commission.**



Summary study status

- Consolidated parameter sets for FCC-hh and FCC-ee machines
- Complete optics baselines for FCC-hh and FCC-ee, beam dynamics compatible with parameter requirements
- Common footprint for both accelerator options
- First round of geology and implementation CE and TI studies completed
- 6 reviews to confirm implementation, layout, optics, hh-injection & rf work

- Convergence on main MDI parameters
- Detector studies ongoing
- Framework available for physics and detector simulations
- FCC-hh physics report being published
- Technologies:
  - SC magnets, cryogenic beam vacuum and cryogenics programs well under way
  - RF, feedback, materials, protection, beam transfer, beam diagnostics moving into focus

Outlook 2016/17

- Further baseline improvement (insertions optimization, MDI optimization, power optimization, …)
- Launch HE-LHC conceptual design effort
- Functional specifications of elements for technical WPs and TI to enable conceptual design work
- Enforce technical infrastructure concepts, integration, installation, safety for machines & detectors
- Continue detector simulations, detector design work and definition of infrastructure requirements
- Development of TDR and construction schedules as basis for cost estimates and governance models
- Study review at FCCW 2017, to freeze baselines

The FCC Week 2016 should:

- Stimulate exchange between participants of all study areas
- Strengthen the collaboration network
- Allow fruitful discussions to develop solutions for our common goals
- Have a Great Week!